Introduction to the Navigation Team

Johnson Space Center EG6 Internship

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Summer 2017

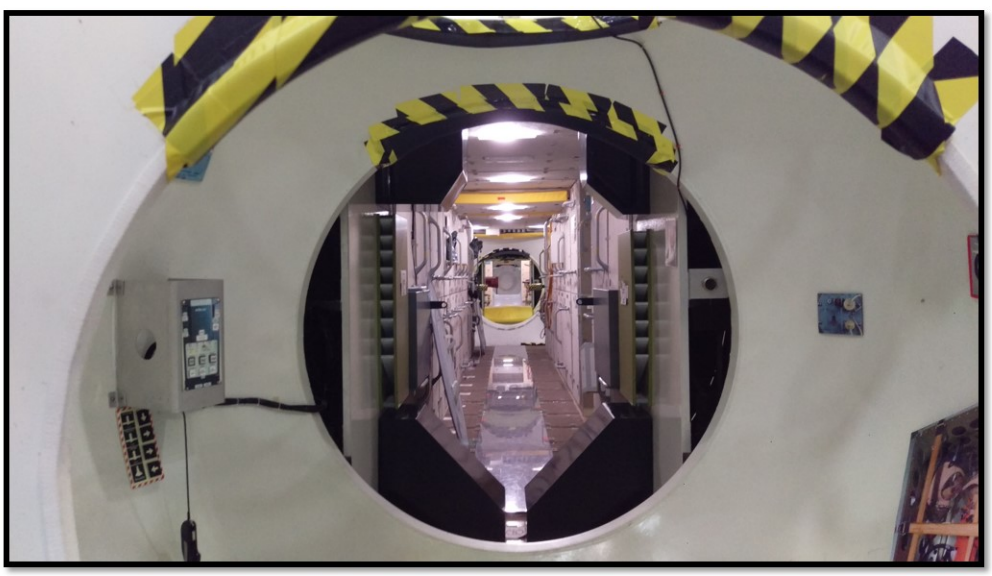

Image from inside the mock ISS.

1 Abstract

The EG6 navigation team at NASA Johnson Space Center, like any team of engineers, interacts with the engineering process from beginning to end; from exploring solutions to a problem, to prototyping and studying the implementations, all the way to polishing and verifying a final flight-ready design. This summer, I was privileged enough to gain exposure to each of these processes, while also getting to truly experience working within a team of engineers. My summer can be broken up into three projects:

i) *Initial study and prototyping:* investigating a manual navigation method that can be utilized onboard Orion in the event of catastrophic failure of navigation systems,

ii) *Finalizing and verifying code:* altering a software routine to improve its robustness and reliability, as well as designing unit tests to verify its performance, and

iii) *Development of testing equipment:* assisting in developing and integrating of a high-fidelity testbed to verify the performance of software and hardware.

2 Initial study and prototyping: Manual Navigation

During the Apollo era, much work was put into determining methods of navigation that would not require significant computational resources in order to develop a backup navigation solution that could be used in the event of catastrophic system failure, specifically addressing the question "Can man navigate in space without the assistance of an electronic computer?" and "What would be the capabilities of such a navigation system?" In my work this summer, I have been tasked with studying the work of Kenneth Nordvedt, Jr., and compile a report that details his process of one- and two-star navigation. The result of Nordtvedt's efforts is a system of exact linear equations that provide a manual navigation solution in the presence of gravity perturbations due to a third body; this navigation solution can be utilized onboard a spacecraft through the use of a sextant type device for measuring angles of either one or two celestial bodies, as well as trigonometric and arithmetic tables to assist in solving any difficult equations.

The technical notes I have generated will be utilized by other interns in implementing this algorithm in code that can be run on the display machines onboard Orion, giving me the experience of being part of a team where I am playing a role upstream of my colleagues, a position that entails its own unique stresses and challenges. This project allowed me to explore a navigation method I was completely unknowledgable about, and gave me an interesting topic to delve into the mathematics and underlying mechanics of the algorithm. Furthermore, I have exercised my communication and technical writing ability knowing that my work needs to be digestable and easily convertable into code, invaluable experience that I don't often get in my typical university research.

3 Finalizing and verifying code: QUEST Algorithm

Attitude estimation is tantamount to any navigation system; the ability to characterize the orientation of a spacecraft is a necessity to perform reliable maneuvers or even to correctly interpret measurements taken by onboard sensors. Magnetospheric, inertial, or even optical data is fairly

meaningless if a system does not have some knowledge as to its attitude relative to these measurement spaces, as the mapping to the state space is undefined without it. This problem of attitude estimation has been well studied due to its strong need, and was formulated by Grace Wahba in 1965 as a minimization of the cost function

$$J(\boldsymbol{A}) = \frac{1}{2}\sum_{k=1}^{N} a_k||\boldsymbol{W}_k - \boldsymbol{A}\boldsymbol{V}_k||^2 \,,$$

where $\boldsymbol{V}_k$ are vectors defined in an inertial reference frame, $\boldsymbol{W}_k$ are observations of these vectors in the relative reference frame, $\boldsymbol{A}$ is the attitude matrix of the spacecraft, and a_k are arbitrary weights. Minimization of this function yeilds the optimal attitude estimate for the spacecraft. This minimization problem, known as the Wahba problem, has since been reformulated in a quaternion perspective by Robert Davenport, which led to Malcolm Shuster's development of his quaternion estimation method in 1979, frequently referred to as QUEST (QUaternion ESTimation), or the q-method.

QUEST is implemented in the Orion optical navigation software as a means of accurately characterizing the interlocking angle between the onboard startrackers and the star camera. Through the use of a series of calibration images, QUEST is able to provide a quaternion average for these images that can be used to process the star camera measurements more precisely. I was tasked this summer with refactoring a C code implementation of QUEST that had been generated using Matlab's autocoder, a very useful functionality of the program but one that is prone to mistakes in code, such as opening vulnerabilities in the code for unforeseen errors, generating code that in some cases might perform incorrectly or inefficiently, or code that is virtually unreadable and therefore difficult for a human to debug. My responsibilities included altering this code to utilize more in-house generated routines (as opposed to the code generated for certain common operations such as matrix multiplication) to increase the readability and develop unit tests that would exercise every line of code, including failure modes. This project has enabled me to refresh my C coding abilities, and has given me a first exposure to developing unit tests, a process I had not gone through before. In addition, reworking this code and the development of these unit tests required me to have a fairly fundamental understanding of the QUEST algorithm, particularly in the case of generating failures to obtain 100% code coverage; this knowledge will be particularly useful, as state estimation plays a large role in a majority in my personal research.

4 Development of testing equipment: OCILOT

The Orion Camera-In-the-Loop Testbed (OCILOT) is a project initiated by the Orion Optical Navigation team to develop a testbed that best mimics a real life scenario to test Orion's optical sensors and optical navigation software. The overarching plan is to work towards a complete closed-loop testbed setup that would allow for active navigation simulations to be performed. The loop is sequenced as:

i) A machine reads in the state of the system (i.e. the position and orientation of the simulated spacecraft, the celestial bodies in the field of view of the spacecraft's camera reference frame, the position of the sun relative to these bodies, and the star map orientation) and uses a program called EDGE to generate a high-fidelity image representative of this system state.

ii) A display loads this image, which is passed through a collimator lens to redirect the light rays emitted from the display such that they hit a camera parallel to one another; this allows the light rays to be received by the camera as if they were emitted from infinitely far away, as is representative of space conditions.

iii) The camera receives a command from the command and control module of the flight software to take an image, which is delivered to the optical navigation algorithm.

iv) The optical navigation software determines a new estimate of the system state based on the image, and delivers this updated state to the EDGE software.

The initial step towards this goal requires a slightly less complicated open-loop system. Instead of the flight software providing EDGE with an updated state, EDGE would be fed a precomputed trajectory and the camera instructed to take images at regular intervals. This allows a series of images to be generated for this data, providing the Optical Navigation group a set of "true" data on which their algorithms can be tested.

My contributions to this project were in the display and camera controller. Due to the cost of collimating lenses, the lens obtained by the Optical Navigation group required a small, yet high-resolution display to load the images. The most appropriate was deemed to be a cell phone, namely a Sony Xperia Z5 Android phone. However, the use of a cellphone as a display presented unique challenges; the phone could not be force-fed images via USB connection, and could not automatically retrieve images from a remote source. Two solutions were designed to circumvent these issues, both requiring Android applications to be developed. The first solution was to meet the necessary conditions for the truth generation setup of OCILOT: an application was developed that allowed for the (preloaded) EDGE generated images to be scrolled through in intervals of arbitrary duration. The second was in support of the future closed-loop setup: a virtual private network (VPN) is set up on the phone to establish a secure shell (SSH) connection with the EDGE machine; through this SSH connection, the phone can monitor the image directory and continuously retrieve and display the most recent image generated by EDGE, allowing for images to be generated and displayed in real-time.

The camera controller for the open-loop setup simply required a C code script that accepted a time interval dictating how frequently to take images and a duration of time to continue taking pictures. Work is still progressing towards supporting the closed-loop setup, but currently the camera listens on a socket for instructions to take an image, then proceeds to record the image in a location. Future work will require the camera controller to respond to the command and control module with the location of the image so that the optical navigation software knows where to retrieve the image from. The current state of the OCILOT setup can be observed in the figure below.

This project has given me more experience with C code and makefiles, different from the QUEST project in that these were generated from scratch. More importantly, in the process of working on the Android application I have learned much of the fundamentals of Java as well as Android application development, two distinct skills that I had no prior experience with. While it won't be particularly of use in my university studies, these languages (in particular, interfacing with remote machines through these languages) will be very interesting to tinker with in my free time, and will undoubtedly prove useful in my professional career later in life.

In addition to the hard skills I have obtained through the duration of this project, I received much experience in my soft-skills as well. Each project I worked on (though primarily OCILOT

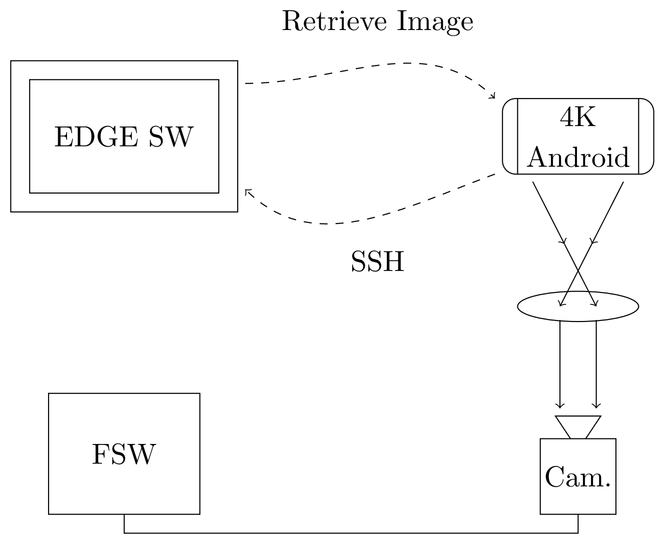

Figure 1. The current status of the OCILOT setup. Note that the 4K Android phone remotely retrieves the images via the SSH connection from the machine running EDGE, displays this image through a collimating lens to parallelize the light rays received by the camera (Cam), which delivers the image to the flight software (FSW).

and QUEST) showed me the diversity of skills present in the Optical Navigation team (navigators, optics specialists, software engineers, and managers); however, OCILOT was unique in that its development seemed solely in the hands of interns. Three of my peers were in charge of updating the EDGE software with the newest star catalog to be used in simulations as well as some other details of the EDGE image generation, the calibration of the camera, and the design of a larger collimating lens to allow for a larger 8K television to be hardwired into the loop to improve image quality and remove the remote connection between the display and the EDGE machine. While the interaction with long-time NASA employees and the relationships I have built with them are invaluable, working with peers in internships like myself is a refreshing exercise that offers its own unique experience.

5 Conclusion

This is my second summer at NASA Johnson Space Center, and has proven to be even more useful than my last. The wide array of projects I worked on have given me more industry experience with some old skills as well as given me some new ones to take back to school with me. Experiences like these always refresh me and give me drive to continue my studies when I get back to my university, however this internship has also given me many more relationships with employees in the EG division and has made me more confident in the decision to strive towards a position with the navigation team at NASA. I hope that these relationships will continue to build, and will assist in me repeating this experience next summer or perhaps in a PATHWAYS position to continue to work towards my career goals.